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BASIC MECHANISMS CONTRIBUTING TO THE HOLLOW CATHODE EFFECT

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INTRODUCTION

If a single plane cathode in a glow discharge is replaced by a cathode with some hollow structure such as a cylindrical or slit shaped hole, then, in a specific range of operating conditions the negative glow is found to be inside the hollow structure of the cathode. Under such conditions at a constant current the voltage is found to be lower and, at a constant voltage, the current is found to be orders of magnitude larger than for the plane cathode. This effect is called the hollow cathode effect (Paschen, 1916).

Many different geometric configurations have been investigated. Some examples are shown in Figure 1. Figure 2 shows the comparison of the discharge characteristics of a planar and a hollow cathode. Often the amplification factor, j/j_o, is used to express the hollow cathode effect, where j_o is the current density of the planar cathode and j the current density of the hollow cathode (Badareu and Waechter, 1958). Figure 3 shows measured amplification factors for two gases and two cathode materials.

Due to the well-defined plasma geometry and the intense emission hollow cathode discharges (HCD) have been used for a long time as spectral lamps (for reviews see S. Caroli, 1985; Mavrodineanu, 1984). For this application hollow cathode discharges are operated usually continuously with currents typically below 1A. Also pulsed hollow cathodes with currents up to kA have been used (Klalkopf, 1971). After the advent of lasers hollow cathodes have immediately been considered as suitable excitation sources for gas lasers (Chebotayev, 1963), again typically with continuous discharges and currents increasing into the 100A regime (for a review see Gerstenberger et al., 1980). Other hollow cathode discharge applications include ion sources (Kuen et al., 1978), plasma jets (Schaefer, 1980), hollow cathode electron beams (Rocca et al., 1987) and plasma contactors (Deininger et al., 1987).

Physics and Applications of Pseudosparks
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More recently, interest in pulsed hollow cathode discharges has significantly increased. Three important applications are mentioned here.

1. Hollow cathode switches are used as high current closing switches (Korzypin et al., 1971). These switches allow high current densities with unheated cathodes without the usual erosion associated with an arc. They, therefore, have greater lifetimes than spark gaps under similar conditions. Hollow cathode switches are usually triggered with a magnetic field as Cross Field Switch Tubes. These devices show excellent operation conditions with respect to fast rep-rated, high current operation, but at this time lack short rise times. Hollow cathodes are utilized in Hollow Anode Thyratrons (Menown and Newton, 1973) which allow operating with high reverse

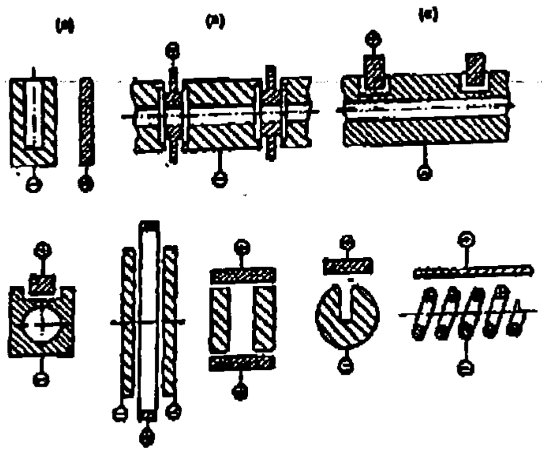

Figure 1. Some typical hollow cathode geometries: a), b), c) cylindrical; d) spherical; e), f) parallel plate; g) slit; h) helical.

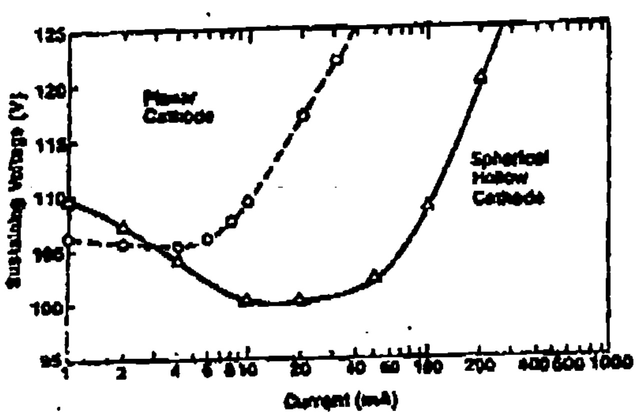

Figure 2. Voltage - current characteristics of a spherical hollow cathode and a planar cathode discharge (Gewartowski and Watson, 1965).

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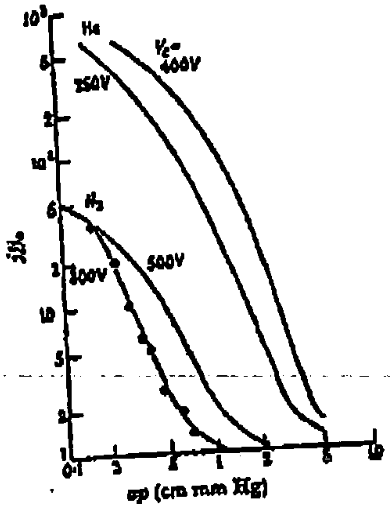

Figure 3. Current amplification factor versus the product of cathode separation for a parallel plate hollow cathode, a, and discharge pressure, p, for Helium and Nitrogen. Lower curve with aluminum electrodes (Little and Engle, 1954), upper curve with iron electrodes (Guentherschulze, 1930).

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currents. More recently, the development of Pseudo Spark Switches (Christiansen and Schultheiss, 1979) has enhanced interest in the hollow cathode effect which is utilized at least during the discharge initiation period. Short risetimes have been achieved with different trigger methods providing preionization (Mechtersheimer et al., 1986; Kirkman and Gunderson, 1986; Circel, 1987).

2. Hollow cathodes are being considered as electrodes for atmospheric pressure diffuse discharge devices such as TEA lasers and diffuse discharge switches (Schaefer et al., 1984). It is assumed that the onset of discharge instabilities is shifted towards higher current densities. However, for these applications, the scaling of hollow cathode operation to high pressures has to be investigated first. For atmospheric pressure the holes should have diameters of the order of a few microns depending on the filling gas.

3. Pulse hollow cathodes are being considered as plasma sources for gas laser systems operating via highly excited states (Falcone and Pedrotti, 1982).

In all of the mentioned applications of pulsed hollow cathodes, the device performance strongly depends on the discharge initiation mechanism and the rise time. In some of the hollow cathode applications as switches currents up to MA have been achieved (Koltypin et al., 1971). Also the transition into the "Superdense Hollow Cathode Glow Discharge" (Abramovich et al., 1966) was discovered and current densities at the cathode surface of up to 10^4 A/cm have been measured (Gunderson). At this time it is not clear whether the basic mechanisms contributing to the "low current density" hollow cathode effect still dominate or at least contribute to the characterization of these discharges or whether these effects play a role only in the initiation phase.

A systematic study and complete understanding of Hollow Cathode Discharges does not exist at this time although a very large number of papers has appeared in the open literature. One reason is that most experimental investigations have been carried out over a narrow range of operating parameters. Another reason is that it is difficult to compare the results obtained with different hollow cathode designs with respect to geometry, dimensions, materials etc., operated with different gases and in different pressure ranges (Kirichenko et al., 1976).

There are several mechanisms contributing to the hollow cathode effect:

1. Electrons emitted from the cathode surface inside the hollow structure which are accelerated in the cathode fall mainly contribute to ionization in the negative glow. Those electrons which have crossed the negative glow without significant energy loss will be reflected at the opposite cathode surface (pendular electrons) and change the potential distribution of the cathode fall. These electrons also contribute to a further enhanced ionization rate in the negative glow (Guentherschulze, 1923; Helm, 1972). This effect significantly influences the electron energy distribution function in the hollow cathode plasma (Borodin and Kagan, 1966; Gill and Webb, 1977).
2. The cathode fall in a hollow cathode under high current density conditions can be significantly thinner than for a plane cathode, reducing the probability for charge transfer collisions. Therefore the average ion velocity at the cathode surface is increased, causing an increased secondary electron emission rate (Bobaderu et al., 1960).
3. Neutral, energetic particles (metastables and photons) generated in the negative glow inside the hollow cathode have a much higher probability of hitting the surface of the cathode due to the hollow geometry, increasing the electron emission rate of the cathode (Little and Engle, 1954). Also more positive ions are lost in the negative glow of a planar electrode since the negative glow is essentially field free and the ion transport is dominated by diffusion, (Sturges and Oskam, 1967).
4. The higher plasma density inside the hollow cathode makes multistep processes more likely (Sturges and Oskam, 1967; Witting, 1971).
5. The confined structure of the hollow cathode leads to a higher density of sputtered atoms of the cathode material with lower ionization potential and in rare gas discharges Penning ionization can occur (Musha, 1962).

All these mechanisms strongly depend on the operation conditions, the hollow cathode geometry, the fill gas, and the cathode material, and it is not clear which mechanism will, in a given device, dominate the hollow cathode effect (Kirichenko et al., 1976). Hollow cathode operation, in general, is restricted to a certain range of pD (1 torr cm $< pD <$ 10 torr cm, for rare gases), where p is the gas pressure and D the diameter of the hollow cathode (Gerwazowski and Watson, 1965). This range is shifted to smaller values of pD if molecular gases are used.

In addition, the motion of the charged particle can be significantly altered using crossed magnetic field. Electrons emitted from the cathode which, without a magnetic field are accelerated away from the cathode surface, now move on cycloid type trajectories with an ExB drift parallel to the cathode

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surface (Metel and Nastyukha, 1981). This shifts the region with the highest ionization and excitation rates closer to the wall. As a consequence, the cathode fall thickness decreases and the impedance of the hollow cathode discharge decreases (Badareu et al., 1967; Tkachenko et al., 1972).

The purpose of this paper is to present an overview of the basic mechanisms contributing to the hollow cathode effect describe experiments which prove the existance and the importance of these effects, and to discuss the relation between these mechanisms and operating conditions and parameters of the discharge.

CURRENT CONTINUITY

Before we discuss the influence of the special geometry on the cathode fall and the negative glow we will briefly summarize the properties of these regions in the abnormal glow discharge. The major properties of these regions is to provide current continuity between cathode and the positive column (see Figure 4).

Electrons emitted from the cathode surface are accelerated in the thin cathode fall region and act as an electron beam. These beam electrons generate a plasma, the negative glow, similar to an electron beam sustained plasma. Typically, approximately half the energy of the initial beam electron is converted into ionization, generating positive ions and low energy thermal electrons, while the other half of the energy is used for various excitation processes. The negative glow is essentially field free which means that the transport of ions and thermalized electrons is dominated by diffusion. Ions which reach the boundary to the cathode fall are accelerated in the cathode fall and their energy at the cathode surface is dominated by the cathode fall voltage and charge exchange collisions with neutrals in the cathode fall region. These ions cause electron emission from the cathode surface. Other mechanisms contributing to electron emission are photoemission caused by UV-radiation emitted from the negative glow and collisions of metastables with the cathode surface. Any change of the current voltage characteristic as experienced when the cathode geometry is changed from a plane cathode to a hollow cathode must therefore change the balance of one or more of these effects. In the following we will discuss some special conditions which are characteristic for hollow cathodes.

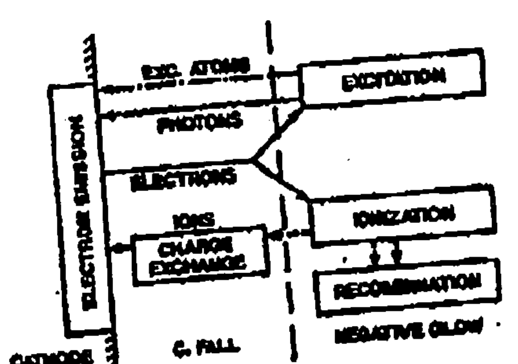

Figure 4. Simplified carrier balance at the cathode